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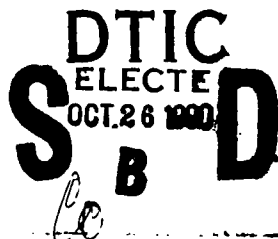
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NONRADIATIVE DIELECTRIC WAVEGUIDE MILLIMETRE-WAVE
INTEGRATED CIRCUITS - A REVIEW

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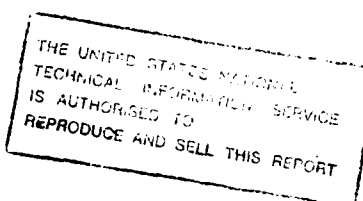
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NONRADIATIVE DIELECTRIC WAVEGUIDE MILLIMETRE-WAVE INTEGRATED CIRCUITS - A REVIEW

Bevan D. Bates and Kym Jordan

ABSTRACT (U)

Nonradiative dielectric waveguide has been shown to be a practical method for the realization of a wide range of millimetre-wave circuit components. However there is still much work to be done before use of this transmission-line media becomes more widespread especially in the areas of active components, design and analysis methods, and fabrication techniques. This report reviews research achievements to date and identifies the important areas requiring further development. *Keywords: Integrated circuits; Dielectric waveguides; Millimeter waves. (RH)*

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1 INTRODUCTION

The use of dielectric waveguides, in particular glass fibres, for the guiding of optical energy is now well established. Dielectric waveguides of several different types also have been investigated for millimetre-wave integrated circuit applications, particularly for application between 40 and 140 GHz. While the physical principles of wave guiding are the same as in optical guide, the dielectric constant of the guide relative to the surrounding media and the fabrication techniques used are generally somewhat different. Waveguiding structures used for millimetre-wave frequencies include (Figure 1): dielectric rod guide, image guide, insulated image guide, strip dielectric guide, inverted strip dielectric guide, H-guide and nonradiative dielectric (NRD) guide [1].
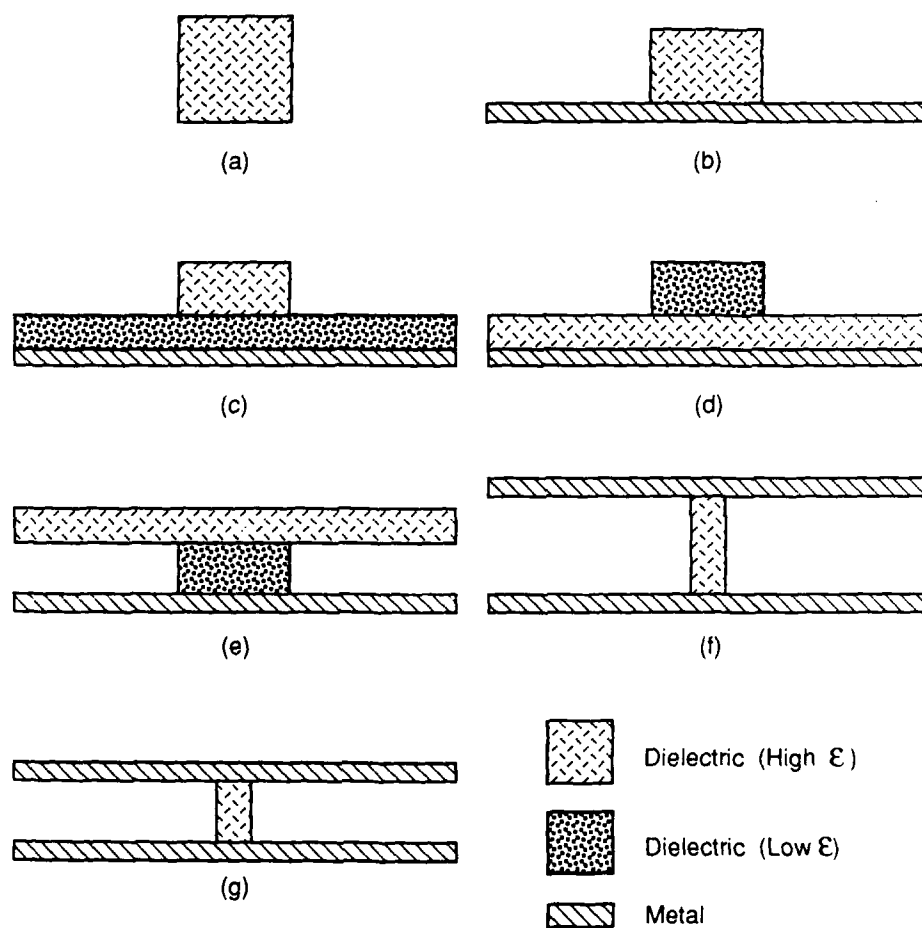
Figure 1   Millimetre-wave dielectric waveguides: (a) dielectric rod guide, (b) image guide, (c) insulated image guide, (d) strip dielectric guide, (e) inverted strip dielectric guide, (f) H-guide and (g) nonradiative dielectric (NRD) guide.

Low-loss materials such as ceramics (ε_r = 4 to 15, where ε_r is the relative dielectric constant), quartz (ε_r = 3.8), castable resins of various dielectric constants, soft substrates (e.g. PTFE-based materials such

as RT Duroid), and semiconductor materials such as Si and GaAs are used. Sections can be either cast, machined or cast and then machined or laser cut. Ceramics can be shaped in the green state and then fired. Thick-film techniques can be used at short millimetre wavelengths.

The principal advantages of dielectric waveguide at millimetre-wave frequencies are:

- Potentially low-cost

- Relatively low manufacturing tolerances required

- Low loss

- Light weight

- Planar (or quasi-planar) structure

- Easy integration with other systems using metal waveguides or stripline type circuits

Nonradiative dielectric waveguide, in which dielectric strips are sandwiched between two parallel plates separated by a distance smaller than half a wavelength was first proposed by Yoneyama and Nishida [2] in 1981. Although the structure is substantially the same as that of the much earlier proposed H-guide [3], the mode of operation and the spacing of the plates is such that bends, junctions and active devices may be incorporated into circuits with very little radiation losses and unwanted coupling to adjacent circuits.

This report first reviews the state-of-the-art of NRD components and circuits and then discusses the important areas requiring research and development.

2 PASSIVE COMPONENTS

2.1 Waveguides

Nonradiative dielectric guide has the configuration shown in Figure 2, consisting of dielectric strips sandwiched between parallel metal plates separated by a distance of less than half a wavelength. The electric field of the operating mode is predominantly parallel to the metal plates. Because the metal plates are separated by less than half a wavelength, waves with the electric field parallel to the plates cannot propagate unless the dielectric strip is present. Fields external to the strip therefore decay rapidly and do not result in loss of energy from the strip by radiation at discontinuities as occurs in many other dielectric waveguiding structures. Modes in NRD guide are hybrid in nature with both electric and magnetic components in the longitudinal direction. The operating mode is the lowest order longitudinal-section magnetic mode (LSM_{01}) in which the magnetic field is parallel to the air-dielectric interfaces (Figure 3).
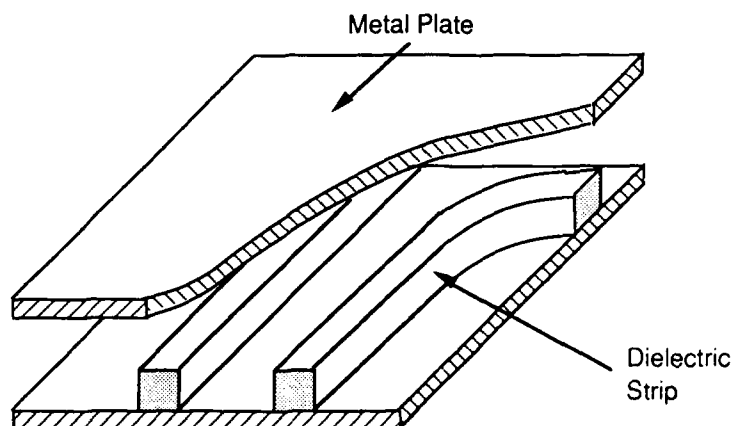
Figure 2   Nonradiative dielectric waveguide [4].

A detailed treatment of the field expressions, the operational diagram for single-mode propagation, the loss characteristics and the bandwidth and dispersion properties of NRD waveguides, including a review of work prior to 1984, has been given by Yoneyama [4]. Theoretical loss calculations showed that the total transmission loss of a suitably designed line was expected to be an order of magnitude less than that of a microstrip line at 50 GHz (typically < 5 $dB.m^{-1}$ for Teflon or alumina). Measured attenuation constants were found to be about 13 $dB.m^{-1}$ for a polystyrene NRD guide and 4 $dB.m^{-1}$ for a Teflon NRD-guide with silver-plated metal plates [5]. A modified structure, known as insulated non-radiative dielectric guide, in which an extra dielectric layer of low dielectric constant is included between the strip and the plates, is predicted to have an attenuation of 2.5 $dB.m^{-1}$ if low-loss alumina is used [6]. The losses for a given structure generally decrease with frequency due to the decreasing proximity of the fields to the metal surfaces (e.g. values calculated at 50 GHz for an alumina guide, show the dielectric loss to be 2 dB and the conduction loss to be 3 dB while at 55 GHz the values are approximately equal at 2 dB).
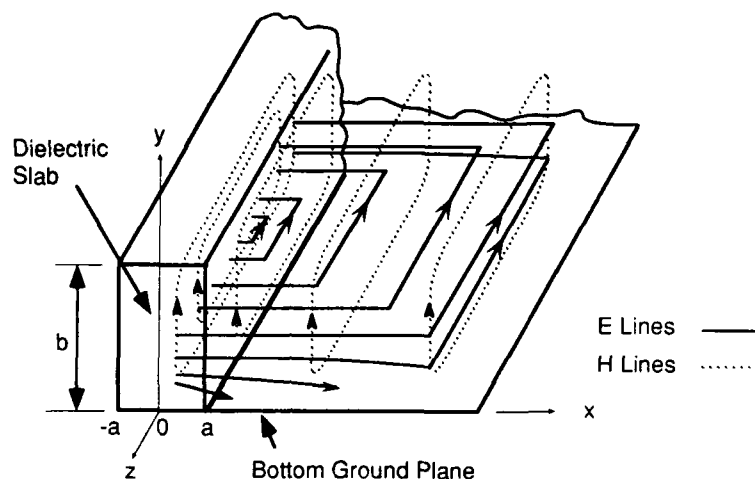
Figure 3   Field configuration in NRD waveguide (after [4]).

Other modified structures include the groove nonradiative dielectric (GNRD) waveguide, and the mono groove NRD (MGNRD) guide. The latter maintains similar performance to the former but is easy to fabricate in the millimetre waveband. Theoretical studies and experimental investigation have been used to characterize the GNRD configuration [7], [8], while the dispersion characteristics of the MGNRD have been analysed using the transverse resonance method [9].

2.2   Bends

Bends are a necessary circuit element for constructing integrated circuits and are usually a problem in dielectric structures because of the resulting loss by radiation. However, as radiation is suppressed in the NRD structure, low-loss bends with a curvature radius as small as one guide wavelength can be achieved, provided the dielectric strip width is optimized for a given curvature radius of the bend at a specified frequency. Coupling theory applied to analyze loss characteristics of the NRD-guide bends has shown that, beside the operating LSM_{01} mode, the parasitic LSE_{01} mode is generated at bends as a result of mode conversion [11]. The field profile at a bend was shown to always shift inwards, confirming a previous experimental prediction [12]. Periodic spikes on previously measured loss-versus-frequency curves of a bend were interpreted as being caused by resonances of the parasitic mode between transition horns fixed at both ends of the bend. As an application of the theory, a 180° bend with a curvature radius of 5 mm was fabricated with polystyrene and tested at 50 GHz. The measured bending loss was less than 0.3 dB [11].

2.3   T-junctions

A high-performance T-junction has been fabricated in which the widths of the main arm and sub-arm were determined experimentally. A dielectric stub and thin-metal patches used as matching elements, proved to be effective in improving the performance. Well-balanced outputs in excess of -4 dB were obtained over a frequency range of 2 GHz at a centre frequency of 35 GHz [13].

2.4 Couplers and power dividers

The rigorous solution for the coupling coefficient of a parallel (uniform) NRD-guide coupler has been obtained from the earlier theory of the double-strip H-guide [14], [2]. Coupling characteristics of non-uniform coupling structures have been predicted by an analytical method. Starting with an approximate but accurate expression for the coupling coefficient between parallel dielectric strips, the scattering coefficients were derived in simple closed-form expressions by taking the effect of the field deformation at the curved sections into account. The coupling coefficient of the nonradiative dielectric waveguide was found to be so large compared to those of other dielectric waveguides that complete power transfer can be attained with coupled polystyrene bends having a curvature radius as small as 20 mm at 50 GHz. The theory was verified experimentally for various coupling structures. 0-dB couplers, quadrature hybrid couplers, and an in-phase power divider were constructed based on the analysis. A comparison of theory and experimental data of these fabricated coupling circuits suggests that the effect of the non-degenerate modes in the straight and curved guides must be included in the analysis to further improve the theory [15]. One possible disadvantage of NRD-guide couplers may be their narrow bandwidth of operation compared to other dielectric waveguide couplers [16]. However techniques are available for making broad-band couplers in dielectric waveguide which also should be applicable to NRD guide [17].

The dispersion characteristics of coupled NRD-guides and the scattering coefficients of NRD-guide directional couplers have been studied theoretically with an experimentally-determined correction factor to account for non-symmetric curved sections. Experimental 3-dB and 10-dB NRD-guide couplers were constructed in Ka-band [18].

Equations have been derived that treat coupled NRD guides terminated in a general reflection coefficient. Two types of coupled line have been evaluated: one with the input and output ports on different lines (series coupled) and the other with the input and output ports on the same line (shunt coupled). Comparisons of calculated versus measured properties were presented. The analysis makes use of flow diagrams to describe the properties of a guide terminated in arbitrary port conditions [19]. Coupled lines of this type have application in filter design [20].

2.5 Filters and resonators

The first reported NRD filter was a two-pole bandpass filter of maximally flat response with a 3 dB bandwidth of 1 GHz at a centre frequency of 50 GHz. The design was based on the metal waveguide evanescent mode filter and consisted of a pair of dielectric chips inserted between input and output strips [21]. A 3-pole 0.1-dB Chebyshev ripple bandpass filter of this structure with 2-percent bandwidth at a centre frequency of 49.5 GHz has been designed and fabricated with Teflon dielectric according to an approximate coupling theory. The calculated and measured filter responses agree quite well, and the excess insertion loss was found to be as small as 0.3 dB. An alternative structure, in which the air gaps were replaced with below-cutoff narrow dielectric strips joining adjacent resonators also achieved satisfactory performance [22] and should be easier to fabricate. A filter of this type has been investigated rigorously by combining a network approach with mode matching theory. Numerical examples were compared with experiment results [23].

In general, filters are designed by using the coupling coefficients of resonators and loaded Q-factors, but theoretical evaluation of these values in NRD is difficult. An experimental design technique for bandpass and band-reject filters has therefore been developed. The theoretical resonance frequency of an isolated resonator is used, but the coupling coefficients and loaded Q-factor are determined by fitting an expression to an experimental curve. As an example, the authors designed and fabricated 3-pole bandpass and bandstop filters having a centre frequency of 49.5 GHz built from circular post resonators of Teflon. Excellent characteristics were realized. The measured value of the insertion loss of the bandpass filter was 0.3 dB and the transmission loss of the bandstop filter was 30 dB [24].

A bandpass filter using round holes drilled through the dielectric has been described. The filter makes use of an inverter-prototype and series full-wave resonators. The T-section inverters were realized by the round holes whose properties are fitted to those of rectangular holes. Closed form equations were obtained using a variational bound analysis. [25]. The measured response was in very good agreement with the predicted theoretical properties [26].

A bandstop filter using side-coupled guides to realize an equivalent of a shunt capacitor and transmission line section has been reported [20]. An alternative structure uses rectangular resonators coupled to the centre dielectric strip. This latter filter has the advantage of simplicity of manufacture, using a centre dielectric of standard cross section. The design procedure is similar to the conventional stripline design procedure, with the stubs replaced by "stubs" of dielectric, or resonators. The design equations for the stub coupling are derived; the properties of the stubs are obtained through measurement [27] or calculated by means of approximate equations assuming that some amount of tuning will be necessary. The resonance is primarily determined by the stub length and not by the tightness of coupling [28].

Ring resonators with band rejection as high as 30 dB have been fabricated [21], [6]. Due to the nonradiative nature of NRD guide, this value is significantly higher than the 15 dB rejection reported for an image line structure [29].

2.6 Transitions

Transitions are essential for accurate measurements using conventional waveguide test equipment. One such transition is shown in Figure 4 consisting of a dielectric strip with an E-plane taper which was inserted into a metal waveguide horn flared in the E-plane and tapered in the H-plane [21]. The minimum return loss was estimated to be 24 dB by using a curve fitting technique to remove the effect of the termination used in the measurement.
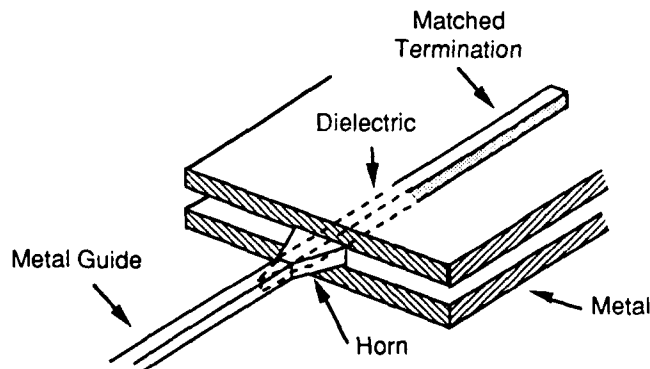
Figure 4   Transition to NRD guide [after 4].

A composite transition theoretically designed to provide both mode matching as well as low reflection coefficient has been described by Malherbe et al. [30]. It consists of a transition from air-filled rectangular w   guide to reduced-width dielectric-filled waveguide, cascaded with a transition to NRD guiu

2.7 Terminations

Matched terminations for NRD guide have been constructed using multilayer resistive film [21] and by inserting a thin NiCr film in the E-plane. The latter approach has been found to be more reliable and achieved a return loss of greater than 20 dB from 34 to greater than 36 GHz [31].

Short-circuit terminations have been made by placing a shorting bar in a slit in the E-plane [4] or by a plate at the end of an open-circuited waveguide [20]. Open circuit terminations are practical because of the non-radiating structure although fringing fields result in a capacitive reactance which is difficult to describe analytically and the open circuited ends couple readily to adjacent fields [19].

2.8   Non-reciprocal devices

A 50 GHz NRD-guide circulator has been developed. A novel mode suppressor was used to reduce unwanted modes to a negligible level and significantly improve the circulator performance. The mode suppressor is a metal patch etched on a thin Teflon substrate and inserted in the vertical midplane (H-plane) of the NRD guide. A quarter-wavelength choke structure suppresses the TEM mode which might otherwise be generated. A half-wavelength step transformer was installed at each port of the circulator to increase the operational bandwidth. The insertion loss of this fabricated circulator was less tl.an 0.3 dB, and the 20 dB isolation bandwidth was about 2.6 GHz. An analysis based on an equivalent circuit representation was used in the design of the circulator [32].

In the circulator, ferrite disc resonators were inserted at the junction of three dielectric strips. Another method of making non-reciprocal devices is to replace the isotropic dielectric of the NRD structure with longitudinally magnetized ferrite. Numerical results for the dispersion of the first few propagation modes in this structure have been presented [33].

3   ANTENNAS

Three types of antennas have been constructed which are directly compatible with NRD guide. These are the slot antenna, the leaky wave antenna, and the rod antenna.

3.1   Slot antennas

A set of theoretical design equations for a slot array fed by NRD waveguide has been developed [34]. Mutual coupling between slots cut into one of the metal walls of the waveguide is taken into consideration. The theoretical development follows that of Elliott [35]. Measurement procedures for obtaining the self-impedance of an isolated inclined radiation slot in the metal wall of a NRD waveguide, needed for the design procedure, are discussed in a companion paper [36]. The design, construction and evaluation of a ten-element input-matched broadside linear array is also described. A slot antenna structure totally compatible with nonradiative dielectric waveguides has been described, consisting of a metal waveguide loaded with coupled dielectric lines feeding a planar slot array machined (or etched) in the surface of the waveguide. The structure is well suited to manufacture at millimetre-wave frequencies [37].

3.2   Leaky-wave antennas

An antenna of simple configuration can be made by truncating the metal plates near the edge of the dielectric strip. This structure has been analysed by using a transverse equivalent network to yield a dispersion relation in closed form. Num ical values have been presented for the phase and leakage constants, including experimental contirmation [38], [39], [40]. Although the structure is intended for millimetre-wave use, measurements were made on a model scaled to X band ($\lambda \approx 3$ cm) to improve the accuracy of the experimental results. The measurements were taken by probing the electric near field strength along the longitudinal direction. Comparisons with accurate theoretical data have been presented for different frequencies and geometrical parameters, and very good agreement was found between the measurements and the theory [41]. A mono groove NRD (MGNRD) leaky-wave antenna of this type has also been constructed, analyzed and tested [9].

A leaky wave antenna has also been constructed by using a dielectric strip of trapezoidal cross section with a metal reflector to obtain unidirectional radiation [42]. This is designed to reduce the cross polarization in the off-axis direction of the antenna.

Another leaky-wave antenna has been constructed by cutting a longitudinal slot in the waveguide side wall. A simple expression for the amount of coupling from the guide was derived using simplifying assumptions. The theoretical coupling values were verified by measurement, and the design, construction, and performance of two leaky-wave antennas was described [43].

The leakage from small air gaps between the top metal plate and the dielectric strip in an NRD guide can cause crosstalk between components, and that from larger gaps can furnish a leaky wave antenna. Theoretical results have been presented for the effect of such an air gap. [44], [45].

3.3   Rod antennas

Two rod antennas specifically for use with NRD guide have been reported. Both use a tapered section to accomplish both impedance and mode matching [46], [47]. The reported gains were 15.9 dB at 9.5 GHz for a 120 mm length and 17.8 dB at 11.5 GHz for a 150 mm length. In the latter antenna, grooves were machined into both of the metal plates to enhance the mechanical stability of the feeding structure. Rexolite was chosen as the dielectric because of its greater rigidity compared with Teflon or polyethylene. Antennas were constructed and polar patterns measured at wavelengths (frequencies) of 3 cm (10 GHz), 3 mm (100 GHz) and 1.3 mm (230 GHz). The rod antenna features a high degree of symmetry in the E and H planes, but have poor cross-polarization characteristics. The structure is also fragile, particularly at short wavelengths.

4 ACTIVE COMPONENTS AND SUBSYSTEMS

4.1 Mixers

A mixer has been constructed using a patch antenna etched on a thin Teflon substrate with a beam lead diode bonded across a gap in the antenna and a quarter-wave choke to suppress RF leakage [31]. The antenna is attached to the transverse plane of the NRD guide strip as shown in Figure 5. In order to achieve good matching between the NRD guide and the diode, a high dielectric constant sheet is inserted in front of the diode, and an air gap, if necessary, is provided at a suitable position on the dielectric strip. A pair of Si mixer diodes were set in a 3-dB coupler to create a balanced mixer. The measured conversion loss of this mixer averaged 6.8 dB over an IF bandwidth of 1 GHz with a 35 GHz LO.
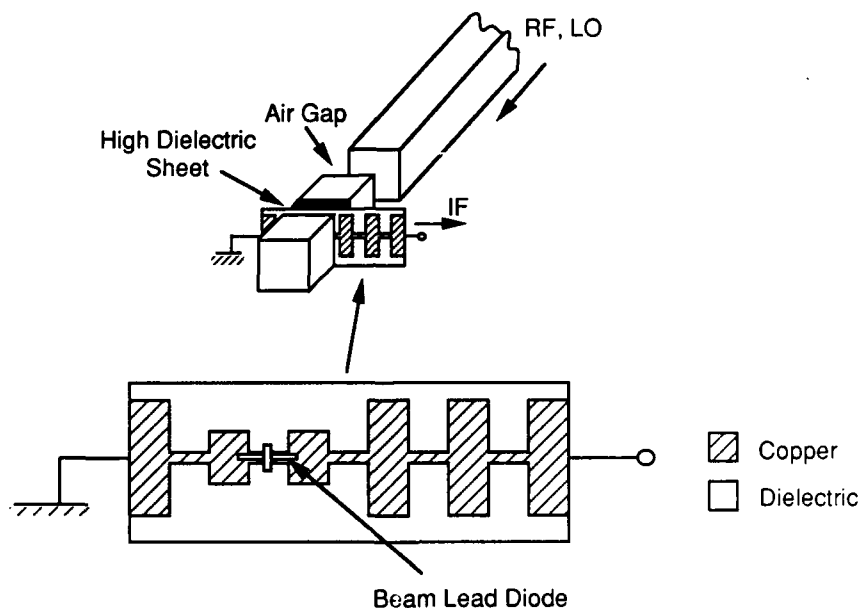
Figure 5   NRD Mixer (after [31]).

A beam-lead mixer, consisting of a diode implanted on a quartz substrate suspended directly in the E-plane of the guided field was reported in [47] but no further details were given.

4.2 Modulators

A p-i-n diode pulse modulator has been fabricated using the same technique as the mixer described above [31]. An on/off ratio of greater than 20 dB was obtained over more than a 1 GHz bandwidth. A slightly different arrangement designed for switching exhibited 1.5 to 2.0 dB insertion loss and more than 25 dB isolation over a 2 GHz bandwidth centred at 35 GHz. Emphasis was placed on the design of a compact, rigid and reliable dipole mount structure [48].

A novel "non-invasive" modulator, consisting of a conventional waveguide modulator coupled to the NRD waveguide by a slot has been described and preliminary results have indicated a maximum of 33 percent pulse modulation [49]. The percentage modulation depends on the size and orientation of the slot.

4.3   Oscillators

A Gunn diode oscillator using a stripline construction for biasing has been described [50]. The diode is mounted so as to feed slots etched in the ground planes of the stripline. One slot couples to the output waveguide, while the other couples to a dielectric stub used as a resonator. The maximum output power obtained was 8.3 mW at approximately 10 GHz.
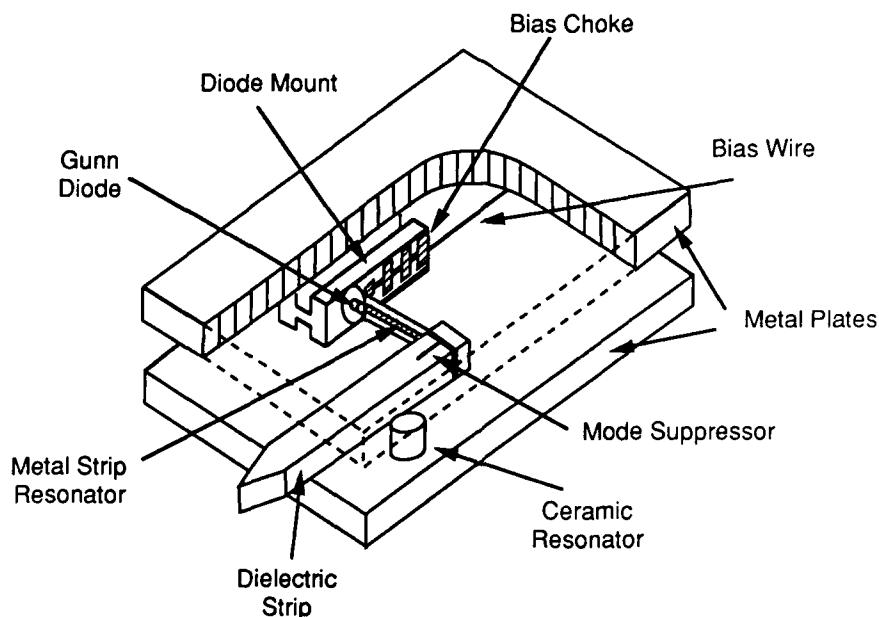
Figure 6   NRD Gunn oscillator (after [31]).

A Gunn oscillator has been constructed with the structure shown in Figure 6 [31]. The diode was fixed to a metal block and biased through a microstrip line with a $\lambda/4$ choke. The RF power was fed to the NRD guide through a stripline resonator etched on a Teflon substrate and glued to the truncated end of the guide. A mode suppressor of the same kind as used in the circulator discussed previously was used to prevent generation of the parasitic LSE_{01} mode. The oscillator performance was stabilized by placing a ceramic resonator of very small temperature coefficient near the dielectric strip. This stabilized the frequency although the output power was reduced from 38 mW to 10 mW.

4.4   Transmitter and receiver subsystems

A complete transmitter and receiver operating at 35 GHz using many of the components described previously has been demonstrated [31]. Transmission testing over a ten month period using the fabricated front ends showed the NRD-guide integrated circuits to be reliable in performance.

5 RESEARCH AND DEVELOPMENT

5.1 Materials and fabrication technology

An important area for investigation is materials and fabrications technology. Many materials have been investigated for use as dielectric materials at microwave and millimetre-wave frequencies. Choice of fabrication processes are closely linked to the choice of material, although the selection also depends on the number of units being produced, accuracy required, and many other factors. The choice of dielectric is largely governed by electrical properties of dielectric constant (ε_r) and loss tangent (tan δ), sometimes referred to as dissipation factor. The choice of conducting planes is largely determined by mechanical considerations of strength and thermal properties. The ultimate choice of NRD guide materials will be a compromise between performance requirements, cost, and fabrication and environment considerations.

5.1.1 Dielectric materials

Most applications of NRD waveguides have to date only achieved experimental or prototype status. No systems or components have been manufactured. This section reviews current materials in use and speculates on future material developments. Fabrication and cost considerations are expected to favour different materials at each stage of development:- experimental, prototype and manufacture.

NRD guide dielectric materials are summarized in Table 1.

material	ε_r	tan δ	rating	cost	fabrication
Plastics					
polystyrene	2.4	10^{-3}	E1, P2	low	easily machined
polyethylene	2.4	10^{-2}	E2	low	easily machined
PTFE	2.1	10^{-4}	E1, P1	high	easily machined
Stycast	2-3.5	10^{-3}	E2, P2	mod	cast / machined
TMM	6.0	10^{-4}	E2, P1	?	machined
Silicon					
glass	4-6		SP	high	cast / ground
fused quartz	3.8		SP	high	cast / ground
Ceramics					
alumina	9.8		SP	high	green machined
Other					
semi-conductor	4.0		SP	high	cast / ground
ceramic filled PTFE	2-10		E2, SP	mod	machined

E=experimental P=prototype SP=special purpose 1=very good 2=good

Table 1   Dielectric materials.

From Table 1 there are good reasons for avoiding most dielectrics for general experimental work. Ceramics and glass are much too hard to fabricate the required waveguide sections. All of the plastics are suitable for experimental work on the grounds of cost, fabrication methods and availability. Polystyrene stands out because of its very low cost ($10 per m^2), availability, and acceptable loss tangent.

For experimental work, plastics can either be machined out of sheet or rod. The plastics group are, in general, lossy dielectrics and although easy and cheap to fabricate, are not suitable for high performance circuits. Polystyrene is acknowledged as the best material

for experimental and some prototype applications and has been used to construct a wide range of passive devices including filters.

PTFE (Teflon) is another preferred dielectric which offers most of the advantages of polystyrene while being one of the lowest loss materials available. The trade off is high cost ($500 per m^2) and undesirable mechanical properties such as creep and bonding difficulties. Waveguides can be easily machined from virgin PTFE sheet. It is also relatively easy to cast resin directly into waveguide shapes. The mechanical problems with PTFE waveguides are exactly those of PTFE microstrip substrate. All the modified PTFE substrate materials i.e. Duroid* and other ceramic filled and glass reinforced substrates are suitable as dielectric waveguide with the qualification that they are more lossy. Yoneyama [4] has suggested that it is practical and cost effective to prototype in polystyrene and to optimize designs in PTFE. Polystyrene and PTFE waveguides are close in dimension as their dielectric constants are similar.

Stycast,[†] (a family of castable epoxy, polyester and silicon resins) can be easily cast, or machined from preformed blanks. The attraction of these materials is their reasonable loss characteristics, well documented electrical and mechanical properties and simple casting techniques. The equipment required to fabricate identical circuits is simply an open or split block mould, vacuum chamber and low temperature oven. The disadvantages of these resins are supply delays, short shelf life and initial cost of a fabrication facility.

Other plastics such as acrylic, acrylonitrile butadiene styrene (ABS), polyethylene and PVC are suitable as experimental waveguides although their high loss characteristics makes them unsuitable for high Q resonant circuits. They are however cheap, readily available, and quite suitable for short transmission paths, couplers and most passive circuits with the exception of filters and resonators.

TMM* (Thermoset microwave material) is a newly announced low loss microwave substrate with a dielectric constant midway between PTFE and ceramic and excellent thermal and mechanical properties. It has been suggested as a promising dielectric waveguide material although, as yet, is not established as a transmission line substrate and therefore little is known as to its practicality. It could however be a promising alternative to PTFE and offers potential for easy reduction of circuit size.

The non-plastic dielectric materials are generally not suitable for general purpose experimental waveguides. The exception to this is cylindrical ceramic resonators. The non-plastic group may however be very suitable for advanced prototype or production devices. They are in general difficult to handle and fabricate and costly for one off or small volume circuits. The silica, quartz group have dielectric constants roughly double those of plastics while the ceramic group are approximately 4 to 5 times greater. Both these groups are commercially available in limited shapes as substrate materials and their high cost is indicative of the very high cost of custom shapes. Some machining (mostly grinding) is possible and this is mainly limited to linear sections but in general profiles must be cast or machined in green state before firing. Preformed waveguide sections are then assembled into circuits like model railway track.

It is reasonable to propose laser scribing of complete circuits from substrate given suitable facilities. Using a high PRF industrial laser with raster scan beam any planar profile could be scribed; even multiple circuits on the same substrate could be produced.

---

* Rogers Corp
† Emerson and Cuming

Some research has been carried out into image guide which is of interest. A technique exists where waveguide is printed on substrate using a thick film technique up to 1 mm thick. The substrate is then fired. No reports of a similar technique being applied to NRD waveguide are known but in concept, image guide techniques should be applicable.

Semiconductor wave guides are also of interest not only as a suitable dielectric material but for their conductive properties when energized either electrically or optically. No reports of semiconductor NRD waveguides are known.

5.1.2 Conducting planes

To date all conducting planes have simply been rigid metal plates between which the dielectric is clamped. Aluminium, brass and plated metals exhibit the good conductivity required of the plates. The plates are often integrated into the housing of the device. For lightweight applications plated fibreglass can be used. For insulated NRD, it may be possible to simply plate the insulation layer. Some designs require slot coupling or slot antennas fabricated in the conducting plane. Other designs may require bias or IF ports through the conducting medium. The ultimate material choice for conducting plane will be dependent on the requirements of good conductivity; rigidity and strength to support dielectric; and ability to be integrated with the total device package.

5.2 Analysis techniques

In addition to the availability of suitable materials and fabrication processes, a key factor in the design of NRD circuits is the availability of suitable analysis techniques and computer-aided design tools to enable circuit designers to rapidly develop new circuits and systems in what, for many, may be an unfamiliar circuit medium.

Common analytical techniques for determining the propagation constant of dielectric guides are the effective dielectric constant (EDC) method and transverse-resonance techniques using the mode-matching method. The EDC method is simple but approximate while the mode-matching technique is rigorous and computationally intensive but provides accurate propagation constants and field distributions for a wide variety of structures. Spectral-domain analyses have found wide application in microstrip and finline structures, and may have some application to dielectric waveguide structures. Analysis techniques which are suitable for research use may not be suitable for routine design work because the speed of execution is inadequate. Therefore it is necessary to develop approximate but accurate techniques based on curve-fitting and table look-up methods to enable interactive design and optimization studies.

The finite element method of analysis has been investigated because of its versatility. Infinite element shape functions, represented by a sum of exponential functions with appropriate decaying factors, were introduced to assure accuracy even if the number of elements is limited. Propagation characteristics in the modified NRD-guides of practical importance were analyzed, and results presented [10].

5.3 Passive components

The major area requiring study is the factors limiting the bandwidth of the components described above and hence develop broadband NRD components. This will include the development of suitable design methodologies for various components such as couplers, filters, T-junctions, terminations and transitions.

5.3.1   Waveguides

A test facility and procedures need to be developed for measurements of waveguide properties such as guide wavelength, attenuation, and dispersion for easy evaluation of the suitability of various materials and possibly to characterize alternate waveguiding structures. This consists primarily of calibrated transitions to standard waveguides and a field probe for measurement of, at least, guide wavelength, and possibly more detailed field patterns. The same facility would also be used in the measurements of the characteristics of various circuit components. For example, measurements need to be made on various bends to confirm the non-radiative nature of the waveguide, to measure the loss and reflections introduced by the bend, and to investigate techniques to reduce or eliminate mode conversion in bends.

5.3.2   Slot coupling

Using slots for coupling between circuit components, for coupling of active devices to waveguide structures and for antennas merits some study because of the ease of integration of slot structures. It is therefore proposed to characterize slots in NRD waveguide by:

1) Measuring the admittance of slots in the metal plates forming the NRD guide. Both thin and thick slots should be studied as many analyses assume the metal is very thin.

2) Measuring the coupling from one NRD guide to another NRD guide on the opposite side of a common metal plate.

3) Studying the use of slot arrays such as a log periodic arrangement for broadband coupling.

4) Measuring the radiation from a single slot and from an array of slots for antenna applications.

Suppression of spurious mode generation at discontinuities is necessary to maintain the non-radiative character of the NRD guide. The use of slots and other techniques for this purpose should be investigated, as successful implementation of many devices depends on this suppression.

5.4   Active components

5.4.1   Detectors

Slots in dielectric image lines employing metallized dielectric substrates as the ground plane have been investigated, and a detector circuit for 26 to 40 GHz has been presented [5¹]. This technique should be adaptable to NRD guide, and generalized to other devices such as mixers and oscillators.

5.4.2   Mixers

The development of broadband mixers is an important goal of future NRD research. Variations of waveguide crossbar mixers should be adaptable to the NRD structure.

5.4.3   Oscillators

The development of local oscillator sources is another objective. Although Gunn oscillators have been reported in the literature, IMPATT and FET devices should also be investigated.

5.5 Subsystems

Attention should be given to developing complete subsystems as early as possible to demonstrate the technology (and to discover the difficulties!). Thus it is proposed to develop a low-cost receiver and transmitter similar to that described by Yoneyama. This could have application as a low-cost communications link or radar system, but at this stage is primarily a technology demonstrator to attract potential sponsors and commercial partners.

6 APPLICATIONS

6.1 Hybrid circuits

One possible application area is low-cost millimetre-wave custom circuits. Fully integrated circuits will continue to remain expensive for some time except for generic circuits required in large numbers. NRD guide could serve as a replacement for microstrip and similar strip transmission lines at shorter millimetre wavelengths where the losses and the tolerances required of strip transmission lines become severe. Active devices (or perhaps modules containing the active devices) could be incorporated into the waveguiding structure during or after manufacture. Replacement of failed devices also may be practical.

6.2 Integrated circuits

Fully integrated circuits may be possible in NRD guide if a suitable semiconductor is used as a dielectric (e.g. GaAs, InP), particularly above 100 GHz. This would only be suitable for high-volume applications in a similar manner to current MMIC technology.

7 CONCLUSIONS

Nonradiative dielectric waveguide has been shown to be a practical method for the realization of a wide range of millimetre-wave circuit components. However there is still much work to be done especially in the areas of active components, design and analysis methods, and fabrication techniques.

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17 SUMMARY OR ABSTRACT
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Nonradiative dielectric waveguide has been shown to be a practical method for the realization of a wide range of millimetre-wave circuit components. However there is still much work to be done before use of this transmission-line media becomes more widespread especialy in the areas of active components, design and analysis methods, and fabrication techniques. This report reviews research achievements to date and identifies the important areas requiring further development.